Introduction to Industrial drives

Primer mover of Industry

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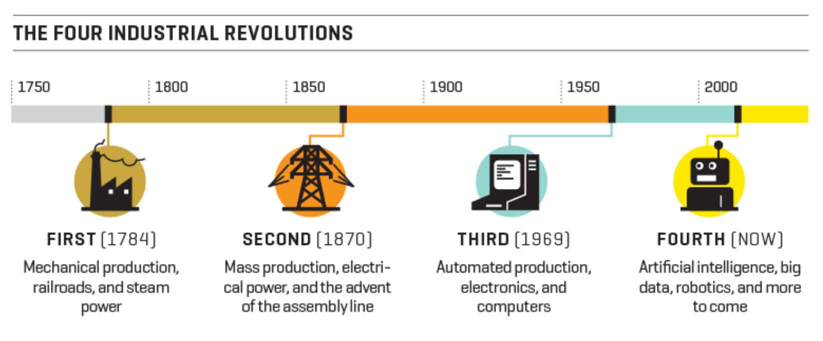
Why Study Industrial Drives?



Why Study AC Drive?

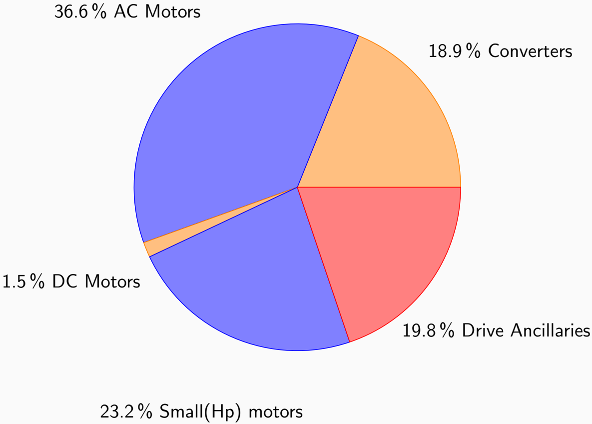
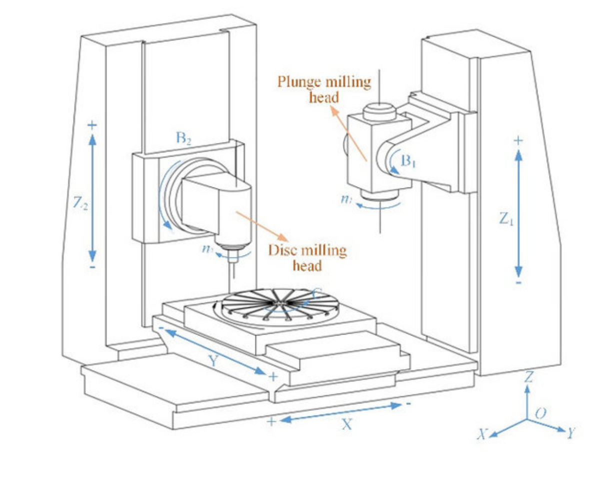


Figure 1: Production share of Electrical drive based on 2009 report by ZVEI

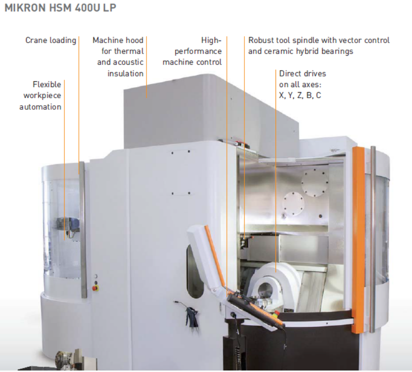
Industrial Applications of Electric Drives

- Chemical Industry - pumps, blowers, mixers
- Pulp, paper, printing - rollers,
- Food & Beverage
- Mining - excavators, conveyors
- Metal Industry - Rollers,
- Machine Shops - CNC, milling, drilling
- Plastics - extruders,
- textiles - rollers
- Oil & Gas - pumps
- Water treatment - pumps

All motions need electric motor drives



High Speed Milling - univerisal appriach to mold-making and production

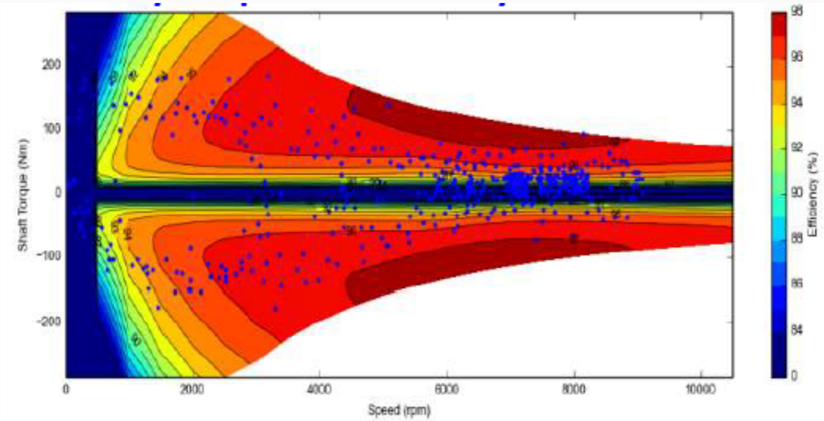


- High frequency spindle drive - speed/power 30,000[rpm]/12[kW]
- Axis acceleration in XYZ 17 [m/s^2]
- Linear velocity 40 [m/min]

Wire Drawing machines

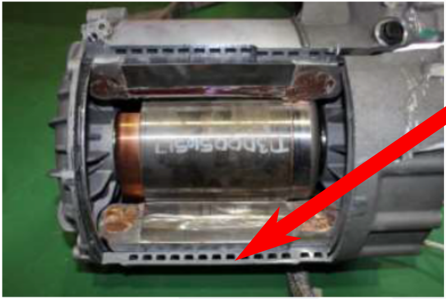
- High speed control 10-12 [m/s]
- Accurate torque control
- Fault Ride Through operation

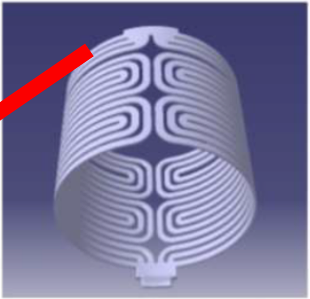
Nissan leaf performance

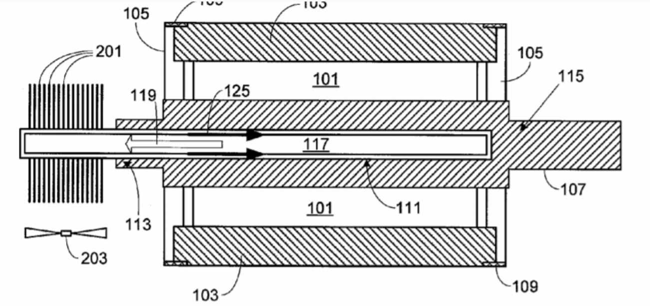


- Uses Interior Permanent Magnet Synchronous Motor
- Field Weakening (FW) range has to be large
- Design of IPM with large FW range is challenge

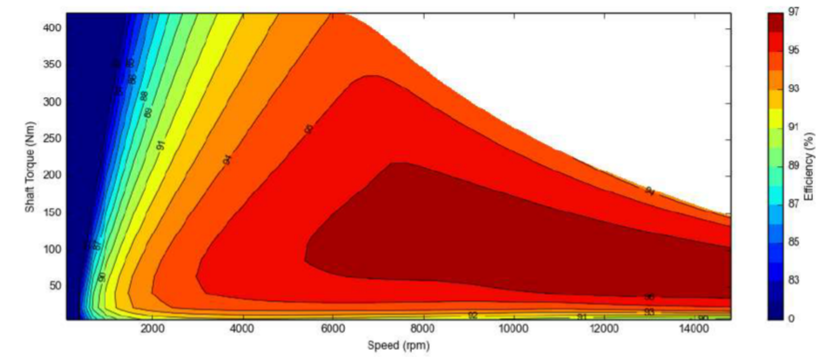
Tesla uses Induction motor





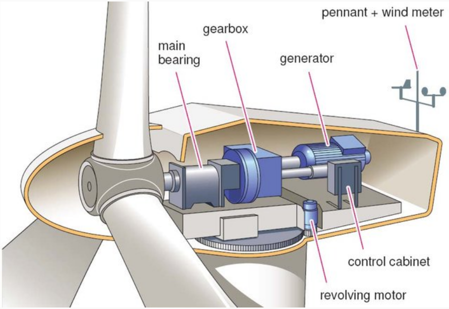


Tesla Performance Curves



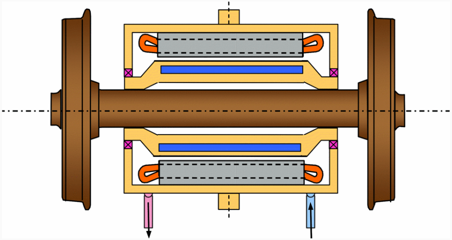
- Induction motor used by Tesla
- Requires control of Torque
- Usually operated in Field-Weakening range

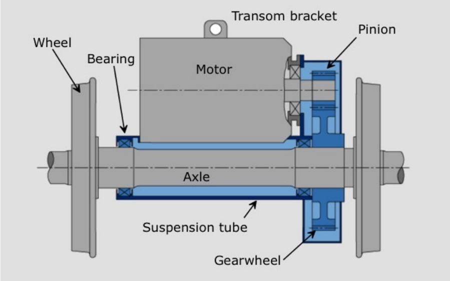
Wind Turbine Drives



- Early schemes used Doubly-Fed Induction Motors
- Induction Motors used with Rotor control
- Permanent Magnet Motors are also used
- Electric Machine acts as Generator
- Power Converters used for Control

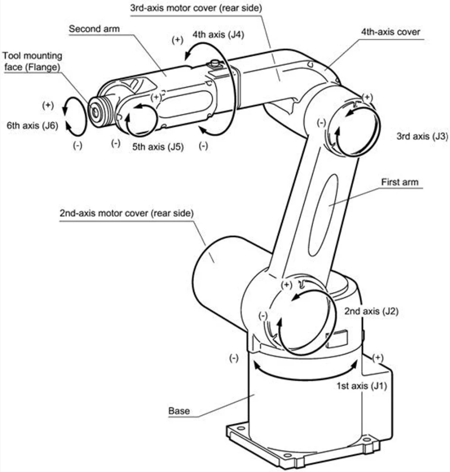
Traction Drives





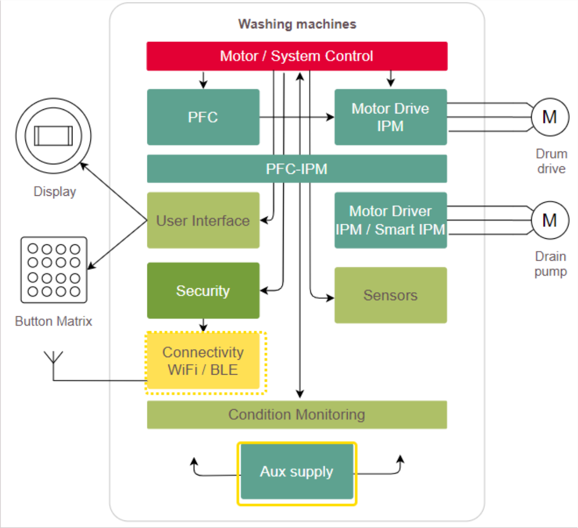
- From MRTs to Shinkansen - Electric Motors needed
- Large Field-weakening range
- Fast Torque control

Robotic Applications



- Requires very good position control
- Cascaded control with inner Torque/Control used
- Machine has to be of small size
- Machine power density has to be high
- Or Torque to weight ratio has to be high

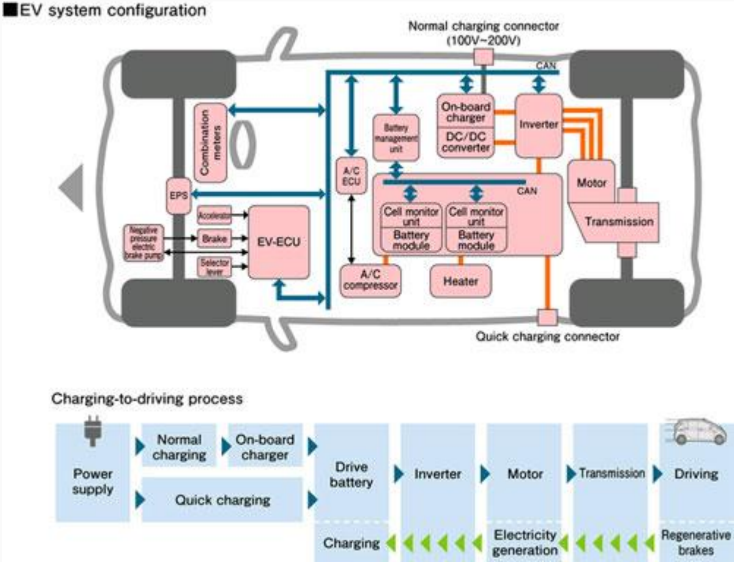
Appliances - Inverter controlled Washing Machine



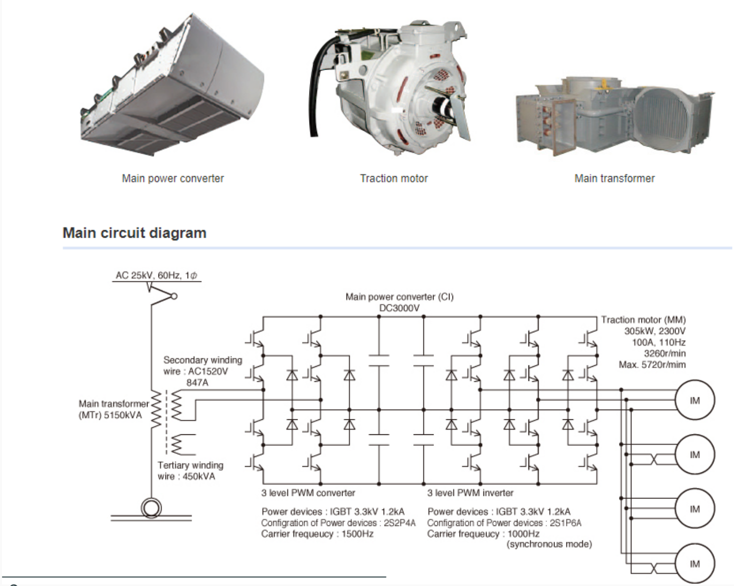
[1]

[1] www.infineon.com/applications

Electric Vehicles and Charging 50kW



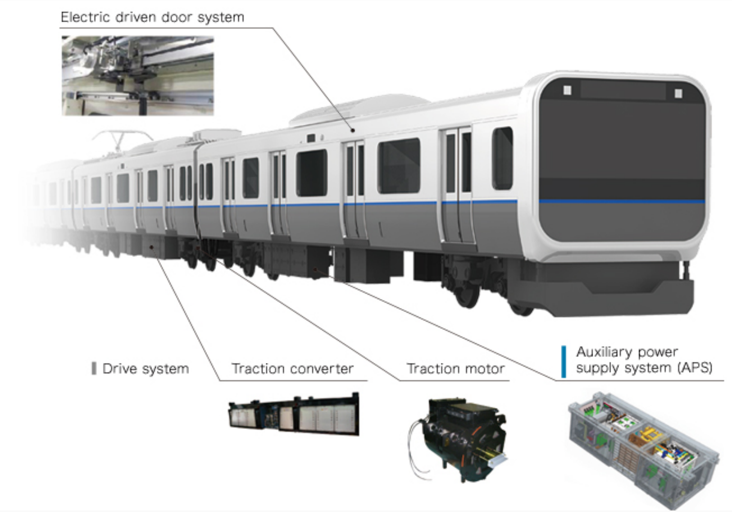
High Speed Rail Applications



[2]

[2] Source:Fuji Electric

MRT Applications



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[3] Source:Fuji Electric

MRT Applications

Cold regions	Kyiv Metro, Ukraine Hokkaido Railway Company
Tropical zone	Singapore Mass Rapid Transit

Americas	Washington D.C. Metro
Europe	Kyiv Metro, Ukraine
Asia	East Japan Railway Company
African Continen	South Africa
Australian Continent	New South Wales (Roof Mount)

Singapore MRT

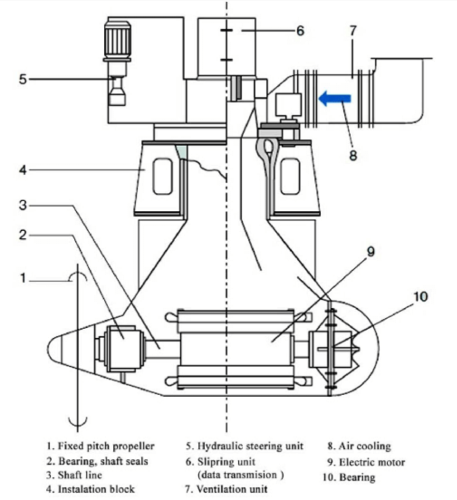
Examples of specification

Car type (Supplied equipment)	Input		Output	Maximum capacity
Electric car (Static inverter)	DC1500V		AC440V, 3φ	260kVA
	DC750V		AC380V, 3φ	130kVA
	AC20/25kV		AC440V, 3φ	180kVA
Diesel train (Engine generator)	Engine generator for propulsion	Variable speed generator	DC24V	8kW※1
		Constant speed generator	AC440V, 3φ	25kVA※2
Passenger coach (Engine generator)	Engine for generator		AC440V, 3φ	440kVA※3

[4]

[4] Source:Fuji Electric

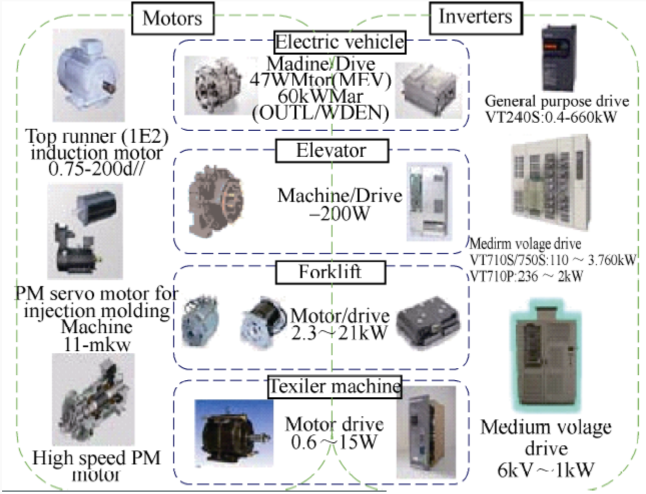
More Electric Ship Propulsions



[a]

[a] Source:ABB Azipod Brochure

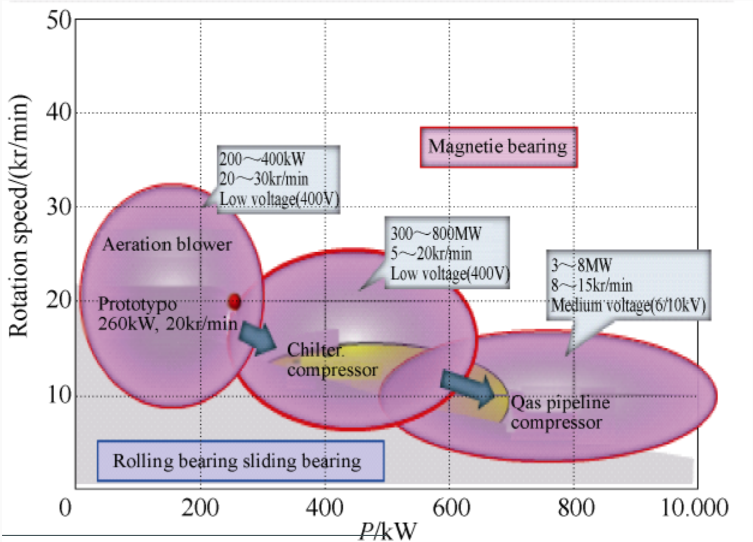
Drive Applications Industry



[5]

[5] K. Matsuse and D. Matsuhashi, "New technical trends on adjustable speed AC motor drives," in Chinese Journal of Electrical Engineering, vol. 3, no. 1, pp. 1-9, 2017, doi: 10.23919/CJEE.2017.7961316.

High Speed PM motor for Industry



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Power Electronics: key enabling technology in Electric Drives

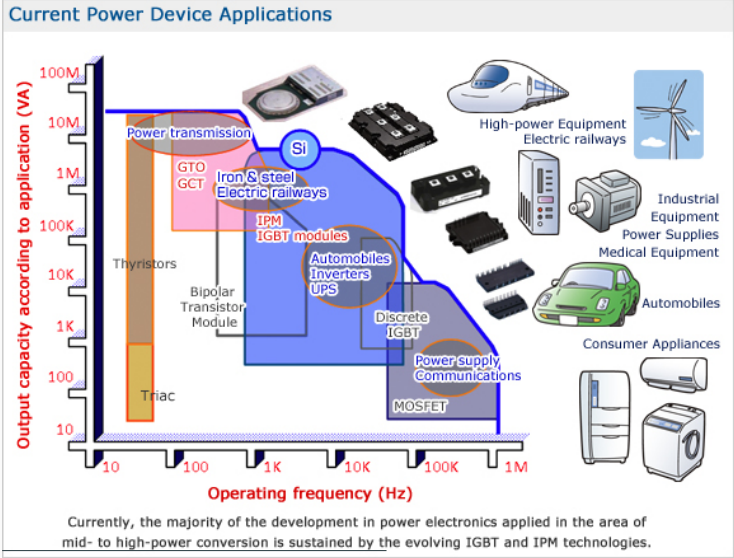
Significant events in motor drive technologies

Year	Technology development
1879	2.2[kW] electric locomotive draws 3 coaches in Berlin industrial exposition
1881	First electric Vehicle with a rechargeable battery as a power source
1948	Transitor was invented at Bell Labs
1956-57	Thyristor (Silicon controlled Rectifier SCR) introduced by GE
1964	Principles of Inverter Circuit was published
1964	First "Shinkansen" with DC drive operated in Japan
1964	EV using Induction motor Thyristor Inverter with silver Zinc battery by GM
1969	Dynamic speed controlled drive
1971	Field-oriented vector control by Siemens
1974	PWM technique for Single-phase converter in Railway
1975	Giant Transistor GTR commercialized (not used after IGBT)
1978	Power MOSFET was introduced
1980	High-Power GTO was commercialized
1987	3 level inverter was introduced
1987	IGBT was commercialized (Inventor got US President Medal)
2012	Large-capacity SiC diode was introduced in rail application

Power Electronics based Variable speed drive

IGBT module

Power Semiconductor Applications



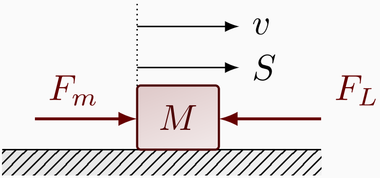
[7]

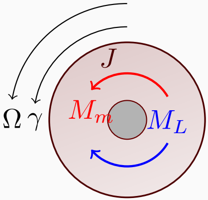
[7] ref source: https://www.mitsubishielectric.com/semiconductors/triple_a_plus/technology/01/index.html

Fundamentals of Electromechanical energy conversion

Basic Forms of Mechanical Drives

Translation





We can write the dynamic equation as

$$F_A = F_m - F_L = M\frac{d^2S}{dt^2} = M\frac{dv}{dt} = M \cdot a$$

Where

S : linear distance [m]
v : linear velocity [m/s]
a : linear acceleration [m/s^2]

Rotational

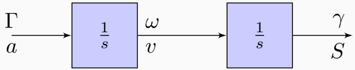
Similarly, we get

$$M_a = M_m - M_L = J\frac{d^2\gamma}{dt^2} = J\frac{d\omega}{dt} = J \cdot \Gamma$$

where

γ : angular distance [radians]
ω : angular velocity [rad/s]
Γ : angular acceleration [rad/s^2]

Modelling the mechanical motions: Signal Flow Graphs



We can model the motions using a set of integrators and sketch am signal flow graph to represent the dynamics

$$\omega = \int \Gamma dt$$

$$\gamma = \int \omega dt$$

and translation motion as

$$v = \int a dt$$

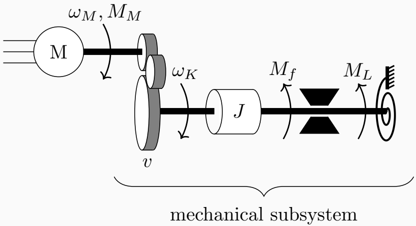
$$S = \int v dt$$

Modelling

- Engineers always create model in order to study and analyse a system
- This models can be described using state variables and an evolution operator
- The evolution operator is a function that tell us how the state variables evolve from one state to another.
- If the state variables are defined continuous in time (at all points), it is called as a *continuous time system*

Rotary motor and its load

A Drive consist of the electric motor that takes in electric power and produces a Torque at the shaft. The shaft is connected to the load through a system of gears and transmission which is the mechanical system.



ω_M : Motor shaft angular velocity [rad/s]
M_M : Motor shaft torque [Nm]
ω_K : Load shaft angular velocity [rad/s]
M_f : Friction torque on load shaft [Nm]
M_L : Load torque on load shaft [Nm]

Equilibrium at motor shaft

For equilibrium, angular acceleration is zero. Hence

$$M_M = M_{L,net}$$

where $M_{L,net}$ is the net load torque seen on motor shaft

Energy and power flow i

Electrical power is supplied to the motor P_e is used to supply the losses in the system and the mechanical load

$$P_e = P_{L,sys} + P_m$$

Electrical power is given as

$$P_e = V \cdot I$$

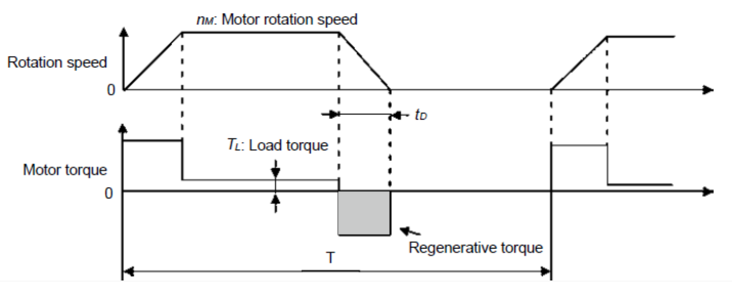
where as mechanical power is given as

$$P_m = M \cdot \omega = F \cdot v$$

this could be for rotary motion or linear motion.

The purpose of the Industrial Drive is to achieve the desired mechanical load profile which is determined by the speed ω of the stem and M_e the motor torque required to achieve it.

Energy and power flow ii



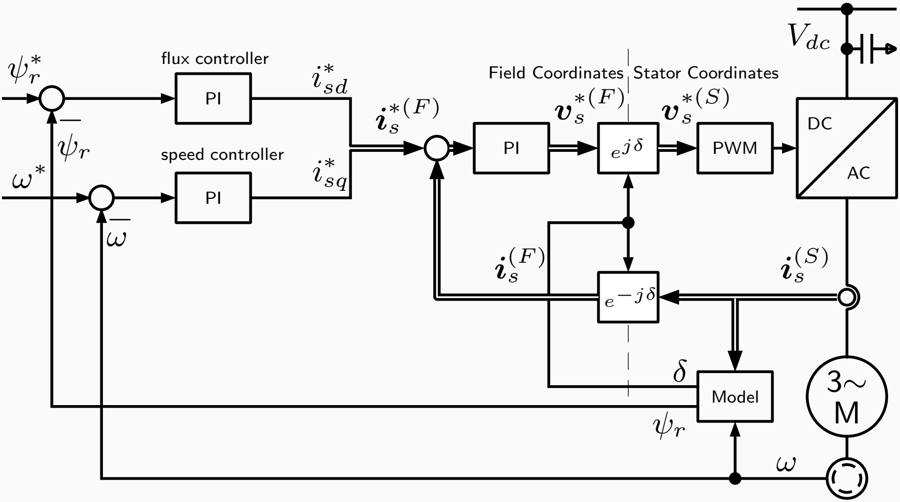
As an Drives Engineer

- You will have to size a drive that meets the velocity, Torque, acceleration requirements of the load machine
- Determine whether it is 4Q operation or 2Q operation
- Determine the best control methods that achieve the velocity, torque and acceleration profile

Energy and power flow iii

- Make sure the temperature ranges of operation
- We can do these things by creating a model of the drive

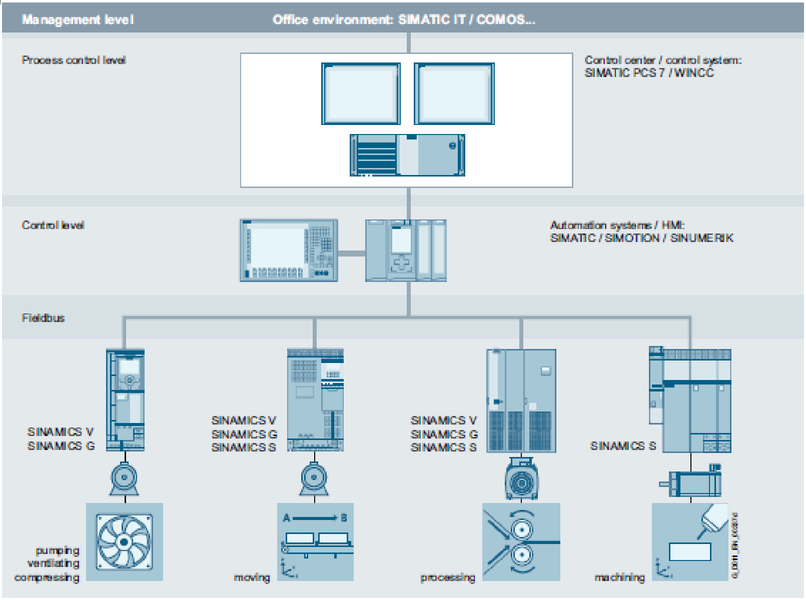
Energy and power flow iv



Energy and power flow v

This is actually a part of a complex chain of controls from the process control plain down to torque control

Energy and power flow vi



Types of Operation in Drives

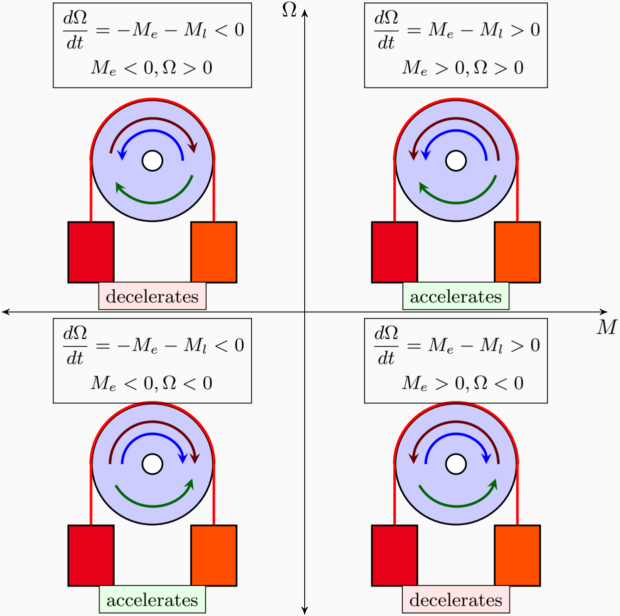
Control in general is of 2 types

1. Open loop Control - Steering, no feedback is used
2. Closed loop control - regulation, feedback is used

- Variable Speed Drive - change speed as per requirement
- Torque Control - change torque as per load requirement
- Speed regulation - maintain constant speed at set point or trajectory
- Position control - change angular position as per reference set point. It can be made to follow a path (linear, sin/cos, parabolic)

For high performance applications closed loop control is used.

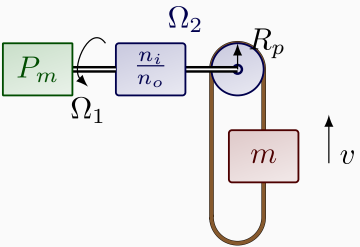
Efficient 4 Quadrant operation in Electric Drives



- Regenerative braking in transportation
- During deceleration energy kinetic energy is converted to electrical (energy recovered from motor)
- To accelerate Electrical energy is fed to motor

Mechatronics design

Elevator: modelling Drives for Elevator applications



Using Energy conservation,

$$\frac{1}{2}J_m\Omega_2^2 = \frac{1}{2}mv^2$$

$$v = R_p\Omega_2$$

$$J_m = mR_p^2$$

$$J_{eq} = J_p + J_m$$

$$J_{eq} = J_p + mR_p^2$$

The moment of inertia reflected on the motor shaft is

$$\begin{aligned} J_L &= \frac{1}{n_g^2}J_{eq} \\ &= \frac{1}{n_g^2}\left(J_p + mR_p^2\right) \end{aligned}$$

The total effective moment of inertia seen by the electric motor is

$$\begin{aligned} J_T &= J_m + J_L \\ &= J_m + \frac{1}{n_g^2}\left(J_p + mR_p^2\right) \end{aligned}$$

where gear ratio is defined as

$$\boxed{n_g = \frac{\text{no. of rotations of driving gear}[n_i]}{\text{no. of rotations of driven gear}[n_o]}}$$

Modelling effective motor dynamics: mechanical i

This total rotational mass is being accelerated, hence the electric motor torque has to balance the accelerating torque and the load torque.

$$\underbrace{M_m}_{MotorTorque} = \underbrace{\frac{d(J_T\Omega_1)}{dt}}_{\text{Accelerating torque}} + \underbrace{M_L}_{\text{net Load toque}} \tag{1}$$

The main dynamics is given by

$$\boxed{\frac{d(J_T \cdot \Omega_m)}{dt} = M_m - M_L = M_a} \tag{2}$$

For constant moment of inertia ($J_T =$ constant), we get

$$\boxed{J_T \frac{d\Omega_m)}{dt} = M_m - M_L = M_a} \tag{3}$$

Modelling effective motor dynamics: mechanical ii

Steps to modelling total moment of inertia on motor

- Sketch a mechanical digram or a free body diagram
- Determine all the translation motion that has to be carried out by motor
- Convert them into equivalent rotational motion
- Add all moment of inertias on same angular velocity
- Convert the inertias using gear ratio to the motor shaft angular velocity Ω_m
- Add the motor moment of inertia to the effective load moment of inertia
- Find the Total moment of inertia that the motor torque has to accelerate

Normalization of Mechanical Dynamics

It is advisable to use normalized values in modelling as they become handy while doing computer control of system. To normalize we use some base values.

M_B : Base Torque, usually rated air-gap torque is taken
N_B : Base speed, usually no-load speed around rated speed is taken
$m = \frac{M_m}{M_B}$: normalized Torque $\Omega_B = 2\pi N_B/60$: Base angular velocity
$\omega = \frac{\Omega_m}{\Omega_b}$: normalized angular velocity

Normalizing the dynamic equation

$$J_T \frac{d\Omega_m}{dt} = M_m - M_L \Bigg| \frac{1}{M_B}$$

$$\frac{J_T \Omega_B}{M_B} \frac{d}{dt}\left(\frac{\Omega_m}{\Omega_b}\right) = \frac{M_m}{M_B} - \frac{M_L}{M_B}$$

$$T_m \frac{d\omega}{dt} = m_m - m_L = m_a$$

Where

$$T_m = \frac{J_T \Omega_B}{M_b} = \frac{[kgm^2][rads^{-1}]}{[Kgf - m \cdot m \cdot s^{-2}]} = [s]$$

is the <u>mechanical or inertial time constant</u>

Mechatronics Design

Crane and Lift Like applications: Dimensioning i

A Crane motor has rated speed of $N_r = 16.67[\mathsf{s}^{-1}]$ and a moment of inertia of $J_M = 6[\mathsf{kgm}^2]$. It drives a gear with gear ratio of $n_g = 30$. The gear has an inertia of $J_G = 3.9[\mathsf{Kg\ m}^2]$ and its efficiecny is $\eta_g = 92\%$. The rope of the crane is wound around a drum of diameter $d_c = 1.2[\mathsf{m}]$. The mass of the rope and the load cage = $m_o = 1000[\mathsf{kg}]$ and the rated load that it can carry is $m_L = 5000[\mathsf{Kg}]$ Find

1. The total moment of Inertia seen by the motor under fully loaded and unloaded conditions
2. What is the operating torque and power supplied by the motor
3. What is the velocity of the cage?
4. What is the value of motor torque, if the upward and downward movement is carried out at $a = \pm 1.5[m/s^2]$ of acceleration and deceleration (Home Work)

Ans:

Crane and Lift Like applications: Dimensioning ii

1.

$$J_T = J_M + J_G + \frac{1}{n_g^2 \eta_g}(m_o + m_L)(\frac{d_c}{2})^2$$

$$J_T = 12.5[\mathsf{kg}\cdot\mathsf{m}^2]$$

with No load

$$J_{To} = J_M + J_G + \frac{1}{n_g^2 \eta_g}(m_o)(\frac{d_c}{2})^2$$

$$J_{To} = 10.33[\mathsf{kg}\cdot\mathsf{m}^2]$$

2. Torque supplied by motor for constant velocity operation

$$M_m = (m_o + m_L)\cdot g\left(\frac{d_c}{2}\right)\frac{1}{n_g \eta_g}$$

$$M_m = 1280 \text{ [Nm]}$$

$$P_m = M_m \cdot 2\pi N_r = 134.1 \text{ [kW]}$$

Crane and Lift Like applications: Dimensioning iii

3. velocity of the load

$$v = N_r \frac{1}{n_g} \cdot \pi d_c = 2.09 \text{ [m/s]}$$

Motors for EV and electric transportation: Example i

Given following data for EV

$m_L = 1200$[kg] : Car mass
$A_f = 1.9$[m^2] : Frontal area
$c_D = 0.45$: Drag coefficient
$w_r = 0.002$: Rolling resistance coefficient
$\eta_g = 0.88$: Gear train efficiency
$v_m = 43$ [m/s] : Maximum velocity (155 kmph)
$\rho_a = 1.2$: Air density

Find

1. The power that has to be supplied by motor at $V_{50} = 13.9$[m/s] and at v_m.
2. At velocity can the EV climb up an incline of elevation 1:15 if we choose a motor of $P_m = 59$[kW]

Motors for EV and electric transportation: Example ii

Ans:

1. The power that has to be supplied by motor is

$$
\begin{aligned}
P_m &= \frac{P_r + P_D}{\eta_g} \\
P_r &= w_r m_L g V \text{ power lost in rolling resistance} \\
P_D &= \frac{1}{2} c_d A_F \rho_a V^3 \\
P_{r50} &= 3.6 \text{ [kW]} \\
P_{rm} &= 11.14 \text{ [kW]} \\
P_{D5o} &= 1.38 \text{ [kW]} \\
P_{Dm} &= 40.8 \text{ [kW]} \\
P_{M50} &= 5.66 \text{ [kW]} \\
P_{Mm} &= 59 \text{ [kW]}
\end{aligned}
$$

Motors for EV and electric transportation: Example iii

To accelerate the EV at maximum velocity v_m we would need a electric motor to have additional power, the accelerating power would decide the final rating of the motor say 60 [kW]

2. What happens when the EV climbs an incline,

$$P_M = \frac{P_{r2} + P_D + P_{ele}}{\eta_g}$$

$$P_{ele} = m_L g sin(\alpha) \cdot V$$

$$P_{r2} = w_r m_L g cos(\alpha) \cdot V$$

$$\alpha = arctan(1/15) = 3.81$$

$$(59000)(0.88) = (1040)v + (0.513)v^3$$

$$v^3 + 2027v - 101208 = 0$$

$$\therefore v = 32.69[m/s]$$

Calculate the velocity in part 2 if the a 80 [kW] motor is selected

Stability of Mechatronic systems

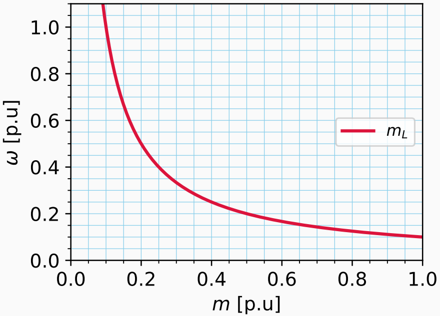
Stability of Mechatronic System

The stable operating point of a mechatronic system is given by

$$\boxed{T_m \frac{d\omega}{dt} = m_e(\omega) - m_L(\omega)}$$

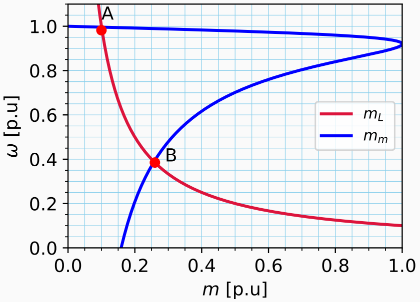
Both motor torque and load torque can change with rotor angular velocity. Take for example Spoolers/Coilers type of load

$$m_L(\omega) = \frac{k}{\omega} \tag{4}$$



Equilibrium Point

If we drive this with an Induction machine, we can plot both the curves and find the equilibrium points



Which of the point in A and B is stable?

The equilibrium points are defined as

$$J_T \frac{d\omega}{dt} = m_m(\omega) - m_L(\omega) \tag{5}$$

$$\frac{d\omega}{dt} = 0 \text{ equilbrium point} \tag{6}$$

$$\therefore m_m(\omega) = m_L(\omega) \tag{7}$$

Two equilibrium points A and B are possible operation

Determine stable point by heuristics

- Take point B, it is a point determined by (ω_B, m_{mB}) for the motor. Let us add a small positive perturbation in angular velocity $\omega_B + \Delta\omega_B$.
- That is, we have moved up vertically. At this upper point, we find what happens to torque

$$m_m(\omega_B + \Delta\omega_B) - m_L(\omega_B + \Delta\omega_B) > 0$$

- Since there will be accelerating torgue, the angular velocity will increase from B and move away from B
- If we consider a perturbation below B, $\omega_B - \Delta\omega_B$, what happens to the accelerating torque
- accelerating torque will become negative

$$m_m(\omega_B + \Delta\omega_B) - m_L(\omega_B + \Delta\omega_B) < 0$$

- Hence the angular velocity will reduce further and move away from B.
- Hence, **B is an unstable equilibrium point**
- What about point A?

Determine the equilibrium point mathematically i

The slope of the speed-torque curve for motor is

$$\boxed{\frac{dm_m(\omega)}{d\omega} = \frac{m_{m2} - m_{m1}}{\omega_2 - \omega_1} = \frac{\Delta m_m}{\Delta \omega}} \tag{8}$$

Similarly, we can define similar curve for the load torque

$$\boxed{\frac{dm_L(\omega)}{d\omega} = \frac{m_{L2} - m_{L1}}{\omega_2 - \omega_1} = \frac{\Delta m_L}{\Delta \omega}} \tag{9}$$

We can write the dynamic equations at the equilibrium points as

$$J_T \frac{d\omega_o}{dt} = m_m(\omega_o) - m_L(\omega_o) \tag{10}$$

$$\frac{d\omega_o}{dt} = 0 \text{ equilbrium point} \tag{11}$$

$$m_m(\omega_o) = m_L(\omega_o) \tag{12}$$

Determine the equilibrium point mathematically ii

If we add a small perturbation $\omega_o + \Delta\omega$, we can linearise the differential equation as

$$J\frac{d\Delta\omega}{dt} = \frac{\partial m_m}{\partial \omega}\Big|_{\omega_o}\Delta\omega - \frac{\partial m_L}{\partial \omega}\Big|_{\omega_o}\Delta\omega \tag{13}$$

In Normal form we can write as

$$\frac{J_T}{k}\frac{d\Delta\omega}{dt} + \Delta\omega = 0 \tag{14}$$

$$k = \frac{\partial}{\partial \omega}(m_L - m_m)\Big|_{\omega_o} \tag{15}$$

$$\frac{d\Delta\omega}{dt} + \frac{1}{T_\omega}\Delta\omega = 0 \tag{16}$$

$$\Delta\omega(t) = k_p e^{-\frac{k}{J_T}t} \tag{17}$$

Determine the equilibrium point mathematically iii

For the ω to return back to equilibrium point

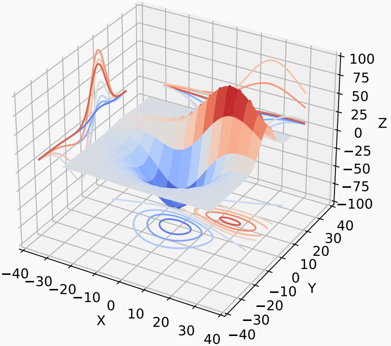
$$\lim_{t \to \infty} \Delta\omega(t) = \begin{cases} 0 & k > 0 \text{ Stable} \\ \infty & k < 0 \text{ unstable} \\ & k = 0 \text{ undetermined} \end{cases} \tag{18}$$

Hence we need to check the relation

$$\boxed{k = \frac{\partial m_L}{\partial \omega} - \frac{\partial m_m}{\partial \omega} > 0}$$

Linearisation of Non-linear systems

Non-linear systems can be linearised at a small operating region



Given a function which depends on parameters (x, y) is represented as

$$z = f(x, y)$$

Suppose we want to linearise it at an operating point (x_o, y_o) we can add a small perturbation around this point $(x_o + \Delta x, y_o + \Delta y)$. We can find the $\Delta z = \frac{\partial F(x,y)}{\partial x \partial y}$ using Taylor's expansions as

$$\Delta z \approx \frac{\partial f(x,y)}{\partial x}\bigg|_{x_o,y_o} (\Delta x) + \frac{\partial f(x,y)}{\partial y}\bigg|_{x_o,y_o} (\Delta y)$$

For a single variable function we will get

$$\Delta z \approx \frac{\partial f(x)}{\partial x}\bigg|_{x_o} \Delta x$$

References i

- R. Krishnan(2017), Electric Drives: modeling, simulation, analysis, design, and applications, press
- W. Leonhard(2001) Control of Electrical Drives, Springer
- A. Binder(2017), Electrical Machines and Drives (*in German*), Springer